

Kaon-nucleon interaction in the extended chiral SU(3) quark model

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Abstract

The chiral SU(3) quark model is extended to include the coupling between the quark and vector chiral fields. The one-gluon exchange (OGE) which dominantly governs the short-range quark-quark interaction in the original chiral SU(3) quark model is now nearly replaced by the vector-meson exchange. Using this model, the isospin $I = 0$ and $I = 1$ kaon-nucleon S, P, D, F wave phase shifts are dynamically studied by solving the resonating group method (RGM) equation. Similar to those given by the original chiral SU(3) quark model, the calculated results for many partial waves are consistent with the experiment, while there is no improvement in this new approach for the P_{13} and D_{15} channels, of which the theoretical phase shifts are too much repulsive and attractive respectively when the laboratory momentum of the kaon meson is greater than 300 MeV.

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I. INTRODUCTION

The kaon-nucleon (KN) scattering process has aroused particular interest in the past and many works have been devoted to this issue [1, 2, 3, 4, 5, 6, 7, 8]. In Ref. [1], the Jülich group presented a meson-exchange model on hadronic degrees of freedom to study the KN phase shifts. Considering single boson exchanges (σ , ρ , and ω) together with contributions from higher-order diagrams involving N , Δ , K , and K^* intermediate states, the authors can give a good description of KN interaction, but the exchange of a short-range (~ 0.2 fm) phenomenological repulsive scalar meson σ_{rep} had to be added in order to reproduce the S -wave phase shifts in the isospin $I = 0$ channel. The range of this repulsion is much smaller than the nucleon size, which clearly shows that the quark substructure of the kaon and nucleon cannot be neglected. Further in Ref. [2] the authors refined this model by replacing the phenomenological σ_{rep} by one-gluon-exchange (OGE), and a satisfactory description of the KN experimental data was gotten. However, in this hybrid model the one-pion exchange is supposed to be absent, which is true on the hadron level, but is not the case in a genuine quark model study, because the quark exchange effect in the single boson exchanges has to be considered. In Ref. [3], Barnes and Swanson used the quark-Born-diagram (QBD) method to derive the KN scattering amplitudes, and obtained reasonable results for the KN phase shifts, but it is limited to S -wave. Subsequently, the Born approximation was applied to investigate the KN scattering more extensively in Ref. [4]. Nevertheless, the magnitudes of most calculated phase shifts are too small. In Ref. [5], taking the π and σ boson exchanges as well as the OGE and confining potential as the quark-quark interactions, the authors calculated the S -wave KN phase shifts in a constituent quark model by using the resonating group method (RGM). The results are too attraction for $I = 0$ channel and too repulsion for $I = 1$ channel, and thus the authors concluded that a consistent description of S -wave KN phase shifts in both isospin $I = 0$ and $I = 1$ channels simultaneously is not possible. In Ref. [6], Lemaire *et al.* studied the KN phase shifts up to the orbit angular momentum $L = 4$ on the quark level by using the RGM method. They only considered the OGE and confining potential as the quark-quark interaction, and their results can give a reasonably description of the S -wave phase shifts, but the P and higher partial waves are poorly described. The authors further incorporated π and σ exchanges besides the OGE and confining potential in the quark-quark interaction in Ref. [7], but the agreement obtained

with the experimental data is quite poor, especially the signs of the S_{01} , P_{03} , P_{11} , D_{05} , D_{13} , D_{15} , F_{07} , and F_{15} waves are opposite to the experiment values. Recently, Wang *et al.* [8] gave a study on the KN elastic scattering in a quark potential model. Their results are consistent with the experimental data, but in their model, a factor of color octet component is added arbitrarily and the size parameter of harmonic oscillator is chosen to be $b_u = 0.255$ fm, which is too small compared with the radius of nucleon.

In spite of great successes, the constituent quark model needs to have a logical explanation, from the underlying theory of the strong interaction [i.e., Quantum Chromodynamics (QCD)] of the source of the constituent quark mass. Thus spontaneous vacuum breaking has to be considered, and as a consequence the coupling between the quark field and the Goldstone boson is introduced to restore the chiral symmetry. In this sense, the chiral quark model can be regarded as a quite reasonable and useful model to describe the medium-range nonperturbative QCD effect. By generalizing the $SU(2)$ linear σ model, a chiral $SU(3)$ quark model is developed to describe the system with strangeness [9]. This model has been quite successful in reproducing the energies of the baryon ground states, the binding energy of deuteron, the nucleon-nucleon (NN) scattering phase shifts of different partial waves, and the hyperon-nucleon (YN) cross sections by performing the RGM calculations [9, 10]. Inspired by these achievements, we try to extend this model to study the baryon-meson interactions. In our previous works [11, 12], we dynamically studied the S -, P -, D -, and F -wave KN phase shifts by performing a RGM calculation. Comparing with Ref. [7], we obtained correct signs of the phase shifts of S_{01} , P_{11} , P_{03} , D_{13} , D_{05} , F_{15} , and F_{07} partial waves, and for P_{01} , D_{03} , and D_{15} channels we also got a considerable improvement in the magnitude. At the same time, the satisfactory results also show that the short-range KN interaction dominantly originates from the quark and one-gluon exchanges.

It is a consensus that constituent quark is the dominant effective degree of freedom for low-energy hadron physics, but about what other proper effective degrees of freedom may be there still has been a debate [13, 14, 15, 16, 17, 18]. Glozman and Riska proposed that the Goldstone boson is the only other proper effective degree of freedom. In Ref. [13, 14], they applied the quark-chiral field coupling model to study the baryon structure, and replaced OGE by vector-meson coupling. They pointed out the spin-flavor interaction is important in explaining the energy of the Roper resonance and got a comparatively good fit to the baryon spectrum. However Isgur gave a critique of the boson exchange model and insisted that the

OGE governs the baryon structure [15, 16]. In Refs. [17, 18], Liu *et al.* produced a valence lattice QCD result which supports the Goldstone boson exchange picture, but Isgur pointed out that this is unjustified [15, 16]. On the other hand, in the study of NN interactions on the quark level, the short-range feature can be explained by OGE interaction and quark exchange effect, while in the traditional one-boson exchange (OBE) model on the baryon level it comes from vector-meson (ρ , K^* , ω , and ϕ) exchange. Some authors also studied the short-range interaction as stemming from the Goldstone boson exchanges on the quark level [10, 19, 20], and it has been shown that these interactions can substitute traditional OGE mechanism. Anyhow, for low-energy hadron physics, what other proper effective degrees of freedom besides constituent quarks may be, whether OGE or vector-meson exchange is the right mechanism for describing the short-range quark-quark interaction, or both of them are important, is still a controversial and challenging problem.

In this paper, we extend the chiral SU(3) quark model to include the coupling between the quark and vector chiral fields. The OGE which dominantly governs the short-range quark-quark interaction in the original chiral SU(3) quark model is now nearly replaced by the vector-meson exchange. As we did in Refs. [11, 12], the mass of the σ meson is taken to be 675 MeV and the mixing of σ_0 (scalar singlet) and σ_8 (scalar iso-scalar) is considered. The set of parameters we used can satisfactorily reproduce the energies of the ground states of the octet and decuplet baryons. Using this model, we perform a dynamical calculation of the S , P , D , F wave KN phase shifts in the isospin $I = 0$ and $I = 1$ channels by solving a RGM equation. The calculated phase shifts for different partial waves are similar to those obtained by the original chiral SU(3) quark model. In comparison with a recent RGM study on a quark level [7], our investigation achieves a considerable improvement on the theoretical phase shifts, and for many channels the theoretical results are qualitatively consistent with the experimental data. Nevertheless there is no improvement in this new approach for the P_{13} and D_{15} partial waves, of which the calculated phase shifts are too much repulsive and attractive respectively when the laboratory momentum of the kaon meson is greater than 300 MeV, as it was the case in the past. It would be studied in future work if there are some physical ingredients missing in our quark model investigations.

The paper is organized as follows. In the next section the framework of the extended chiral SU(3) quark model is briefly introduced. The results for the S -, P -, D -, and F -wave KN phase shifts are shown in Sec. III, where some discussion is presented as well. Finally,

the summary is given in Sec. IV.

II. FORMULATION

A. Model

The chiral SU(3) quark model has been widely described in the literature [11, 12] and we refer the reader to those works for details. Here we just give the salient features of the extended chiral SU(3) quark model.

In the extended chiral SU(3) quark model, besides the nonet pseudoscalar meson fields and nonet scalar meson fields, the couplings among vector meson fields with quarks is also considered. With this generalization, in the interaction Lagrangian a term of coupling between the quark and vector meson field is introduced,

$$\mathcal{L}_I^v = -g_{chv}\bar{\psi}\gamma_\mu T^a A_a^\mu \psi - \frac{f_{chv}}{2M_P}\bar{\psi}\sigma_{\mu\nu}T^a\partial^\nu A_a^\mu \psi. \quad (1)$$

Thus the meson fields induced effective quark-quark potentials can be written as

$$V_{ij}^{ch} = \sum_{a=0}^8 V_{\sigma_a}(\mathbf{r}_{ij}) + \sum_{a=0}^8 V_{\pi_a}(\mathbf{r}_{ij}) + \sum_{a=0}^8 V_{\rho_a}(\mathbf{r}_{ij}), \quad (2)$$

where $\sigma_0, \dots, \sigma_8$ are the scalar nonet fields, π_0, \dots, π_8 the pseudoscalar nonet fields, and ρ_0, \dots, ρ_8 the vector nonet fields. The expressions of these potentials are

$$V_{\sigma_a}(\mathbf{r}_{ij}) = -C(g_{ch}, m_{\sigma_a}, \Lambda)X_1(m_{\sigma_a}, \Lambda, r_{ij})[\lambda_a(i)\lambda_a(j)] + V_{\sigma_a}^{l\cdot s}(\mathbf{r}_{ij}), \quad (3)$$

$$V_{\pi_a}(\mathbf{r}_{ij}) = C(g_{ch}, m_{\pi_a}, \Lambda)\frac{m_{\pi_a}^2}{12m_{q_i}m_{q_j}}X_2(m_{\pi_a}, \Lambda, r_{ij})(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j)[\lambda_a(i)\lambda_a(j)] + V_{\pi_a}^{ten}(\mathbf{r}_{ij}), \quad (4)$$

$$V_{\rho_a}(\mathbf{r}_{ij}) = C(g_{chv}, m_{\rho_a}, \Lambda) \left\{ X_1(m_{\rho_a}, \Lambda, r_{ij}) + \frac{m_{\rho_a}^2}{6m_{q_i}m_{q_j}} \left(1 + \frac{f_{chv}}{g_{chv}} \frac{m_{q_i} + m_{q_j}}{M_P} + \frac{f_{chv}^2}{g_{chv}^2} \right. \right. \\ \left. \left. \times \frac{m_{q_i}m_{q_j}}{M_P^2} \right) X_2(m_{\rho_a}, \Lambda, r_{ij})(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) \right\} [\lambda_a(i)\lambda_a(j)] + V_{\rho_a}^{l\cdot s}(\mathbf{r}_{ij}) + V_{\rho_a}^{ten}(\mathbf{r}_{ij}), \quad (5)$$

with

$$V_{\sigma_a}^{l\cdot s}(\mathbf{r}_{ij}) = -C(g_{ch}, m_{\sigma_a}, \Lambda)\frac{m_{\sigma_a}^2}{4m_{q_i}m_{q_j}} \left\{ G(m_{\sigma_a}r_{ij}) - \left(\frac{\Lambda}{m_{\sigma_a}} \right)^3 G(\Lambda r_{ij}) \right\} \\ \times [\mathbf{L} \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)][\lambda_a(i)\lambda_a(j)], \quad (6)$$

$$\begin{aligned}
V_{\rho_a}^{l\cdot s}(\mathbf{r}_{ij}) &= -C(g_{chv}, m_{\rho_a}, \Lambda) \frac{3m_{\rho_a}^2}{4m_{q_i}m_{q_j}} \left(1 + \frac{f_{chv}}{g_{chv}} \frac{2(m_{q_i} + m_{q_j})}{3M_P} \right) \\
&\times \left\{ G(m_{\rho_a}r_{ij}) - \left(\frac{\Lambda}{m_{\rho_a}} \right)^3 G(\Lambda r_{ij}) \right\} [\mathbf{L} \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)][\lambda_a(i)\lambda_a(j)], \quad (7)
\end{aligned}$$

and

$$V_{\pi_a}^{ten}(\mathbf{r}_{ij}) = C(g_{ch}, m_{\pi_a}, \Lambda) \frac{m_{\pi_a}^2}{12m_{q_i}m_{q_j}} \left\{ H(m_{\pi_a}r_{ij}) - \left(\frac{\Lambda}{m_{\pi_a}} \right)^3 H(\Lambda r_{ij}) \right\} \hat{S}_{ij}[\lambda_a(i)\lambda_a(j)], \quad (8)$$

$$\begin{aligned}
V_{\rho_a}^{ten}(\mathbf{r}_{ij}) &= -C(g_{chv}, m_{\rho_a}, \Lambda) \frac{m_{\rho_a}^2}{12m_{q_i}m_{q_j}} \left(1 + \frac{f_{chv}}{g_{chv}} \frac{m_{q_i} + m_{q_j}}{M_P} + \frac{f_{chv}^2}{g_{chv}^2} \frac{m_{q_i}m_{q_j}}{M_P^2} \right) \\
&\times \left\{ H(m_{\pi_a}r_{ij}) - \left(\frac{\Lambda}{m_{\pi_a}} \right)^3 H(\Lambda r_{ij}) \right\} \hat{S}_{ij}[\lambda_a(i)\lambda_a(j)], \quad (9)
\end{aligned}$$

where

$$C(g_{ch}, m, \Lambda) = \frac{g_{ch}^2}{4\pi} \frac{\Lambda^2}{\Lambda^2 - m^2} m, \quad (10)$$

$$X_1(m, \Lambda, r) = Y(mr) - \frac{\Lambda}{m} Y(\Lambda r), \quad (11)$$

$$X_2(m, \Lambda, r) = Y(mr) - \left(\frac{\Lambda}{m} \right)^3 Y(\Lambda r), \quad (12)$$

$$Y(x) = \frac{1}{x} e^{-x}, \quad (13)$$

$$G(x) = \frac{1}{x} \left(1 + \frac{1}{x} \right) Y(x), \quad (14)$$

$$H(x) = \left(1 + \frac{3}{x} + \frac{3}{x^2} \right) Y(x), \quad (15)$$

$$\hat{S}_{ij} = [3(\boldsymbol{\sigma}_i \cdot \hat{r}_{ij})(\boldsymbol{\sigma}_j \cdot \hat{r}_{ij}) - \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j], \quad (16)$$

and M_P being a mass scale, taken as proton mass. m_{σ_a} is the mass of the scalar meson, m_{π_a} the mass of the pseudoscalar meson, and m_{ρ_a} the mass of the vector meson.

For the systems with an antiquark \bar{s} , the total Hamiltonian can be written as

$$H = \sum_{i=1}^5 T_i - T_G + \sum_{i<j=1}^4 V_{ij} + \sum_{i=1}^4 V_{i\bar{5}}, \quad (17)$$

where T_G is the kinetic energy operator for the center-of-mass motion, and V_{ij} and $V_{i\bar{5}}$ represent the quark-quark (qq) and quark-antiquark ($q\bar{q}$) interactions, respectively,

$$V_{ij} = V_{ij}^{OGE} + V_{ij}^{conf} + V_{ij}^{ch}, \quad (18)$$

where V_{ij}^{OGE} is the one-gluon-exchange interaction,

$$V_{ij}^{OGE} = \frac{1}{4} g_i g_j (\lambda_i^c \cdot \lambda_j^c) \left\{ \frac{1}{r_{ij}} - \frac{\pi}{2} \delta(\mathbf{r}_{ij}) \left(\frac{1}{m_{q_i}^2} + \frac{1}{m_{q_j}^2} + \frac{4}{3} \frac{1}{m_{q_i} m_{q_j}} (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) \right) \right\} + V_{OGE}^{l\cdot s}, \quad (19)$$

with

$$V_{OGE}^{l\cdot s} = -\frac{1}{16} g_i g_j (\lambda_i^c \cdot \lambda_j^c) \frac{3}{m_{q_i} m_{q_j}} \frac{1}{r_{ij}^3} \mathbf{L} \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j), \quad (20)$$

and V_{ij}^{conf} is the confinement potential, taken as the quadratic form,

$$V_{ij}^{conf} = -a_{ij}^c (\lambda_i^c \cdot \lambda_j^c) r_{ij}^2 - a_{ij}^{c0} (\lambda_i^c \cdot \lambda_j^c). \quad (21)$$

$V_{i\bar{5}}$ in Eq. (17) includes two parts: direct interaction and annihilation parts,

$$V_{i\bar{5}} = V_{i\bar{5}}^{dir} + V_{i\bar{5}}^{ann}, \quad (22)$$

with

$$V_{i\bar{5}}^{dir} = V_{i\bar{5}}^{conf} + V_{i\bar{5}}^{OGE} + V_{i\bar{5}}^{ch}, \quad (23)$$

where

$$V_{i\bar{5}}^{conf} = -a_{i\bar{5}}^c (-\lambda_i^c \cdot \lambda_{\bar{5}}^{c*}) r_{i\bar{5}}^2 - a_{i\bar{5}}^{c0} (-\lambda_i^c \cdot \lambda_{\bar{5}}^{c*}), \quad (24)$$

$$\begin{aligned} V_{i\bar{5}}^{OGE} = & \frac{1}{4} g_i g_s (-\lambda_i^c \cdot \lambda_{\bar{5}}^{c*}) \left\{ \frac{1}{r_{i\bar{5}}} - \frac{\pi}{2} \delta(\mathbf{r}_{i\bar{5}}) \left(\frac{1}{m_{q_i}^2} + \frac{1}{m_s^2} + \frac{4}{3} \frac{1}{m_{q_i} m_s} (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_5) \right) \right\} \\ & - \frac{1}{16} g_i g_s (-\lambda_i^c \cdot \lambda_{\bar{5}}^{c*}) \frac{3}{m_{q_i} m_{q_5}} \frac{1}{r_{i\bar{5}}^3} \mathbf{L} \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_5), \end{aligned} \quad (25)$$

and

$$V_{i\bar{5}}^{ch} = \sum_j (-1)^{G_j} V_{i\bar{5}}^{ch,j}. \quad (26)$$

Here $(-1)^{G_j}$ represents the G parity of the j th meson. For the NK system, $u(d)\bar{s}$ can only annihilate into K and K^* mesons—i.e.,

$$V_{i\bar{5}}^{ann} = V_{ann}^K + V_{ann}^{K^*}, \quad (27)$$

with

$$V_{ann}^K = C^K \left(\frac{1 - \boldsymbol{\sigma}_q \cdot \boldsymbol{\sigma}_{\bar{q}}}{2} \right)_s \left(\frac{2 + 3\lambda_q \cdot \lambda_{\bar{q}}^*}{6} \right)_c \left(\frac{38 + 3\lambda_q \cdot \lambda_{\bar{q}}^*}{18} \right)_f \delta(\mathbf{r}), \quad (28)$$

and

$$V_{ann}^{K^*} = C^{K^*} \left(\frac{3 + \boldsymbol{\sigma}_q \cdot \boldsymbol{\sigma}_{\bar{q}}}{2} \right)_s \left(\frac{2 + 3\lambda_q \cdot \lambda_{\bar{q}}^*}{6} \right)_c \left(\frac{38 + 3\lambda_q \cdot \lambda_{\bar{q}}^*}{18} \right)_f \delta(\mathbf{r}), \quad (29)$$

where C^K and C^{K^*} are treated as parameters and we adjust them to fit the mass of K and K^* mesons.

B. Determination of the parameters

The harmonic-oscillator width parameter b_u is taken with different values for the two models: $b_u = 0.50$ fm in the chiral SU(3) quark model and $b_u = 0.45$ fm in the extended chiral SU(3) quark model. This means that the bare radius of baryon becomes smaller when more meson clouds are included in the model, which sounds reasonable in the sense of the physical picture. The up (down) quark mass $m_{u(d)}$ and the strange quark mass m_s are taken to be the usual values: $m_{u(d)} = 313$ MeV and $m_s = 470$ MeV. The coupling constant for scalar and pseudoscalar chiral field coupling, g_{ch} , is determined according to the relation

$$\frac{g_{ch}^2}{4\pi} = \left(\frac{3}{5} \right)^2 \frac{g_{NN\pi}^2}{4\pi} \frac{m_u^2}{M_N^2}, \quad (30)$$

with empirical value $g_{NN\pi}^2/4\pi = 13.67$. g_{chv} and f_{chv} are the coupling constants for vector coupling and tensor coupling of the vector meson field, respectively. In the study of nucleon resonance transition coupling to vector meson, Riska and Brown took $g_{chv} = 3.0$ and neglected the tensor coupling part [21]. From the one-boson exchange theory on the baryon level, we can also obtain these two values according to the SU(3) relation between quark and baryon levels. For example,

$$g_{chv} = g_{NN\rho}, \quad (31)$$

TABLE I: Model parameters. The meson masses and the cutoff masses: $m_{a_0} = 980$ MeV, $m_\kappa = 1430$ MeV, $m_{f_0} = 980$ MeV, $m_\pi = 138$ MeV, $m_K = 495$ MeV, $m_\eta = 549$ MeV, $m_{\eta'} = 957$ MeV, $m_\rho = 770$ MeV, $m_{K^*} = 892$ MeV, $m_\omega = 782$ MeV, $m_\phi = 1020$ MeV, $\Lambda = 1500$ MeV for κ and 1100 MeV for other mesons.

	Chiral SU(3) quark model		Extended chiral SU(3) quark model	
	I	II	I	II
	$\theta^S = 35.264^\circ$	$\theta^S = -18^\circ$	$\theta^S = 35.264^\circ$	$\theta^S = -18^\circ$
b_u (fm)	0.5	0.5	0.45	0.45
m_u (MeV)	313	313	313	313
m_s (MeV)	470	470	470	470
g_u^2	0.7704	0.7704	0.0748	0.0748
g_s^2	0.5525	0.5525	0.0001	0.0001
g_{ch}	2.621	2.621	2.621	2.621
g_{chv}	0	0	2.351	2.351
m_σ (MeV)	675	675	675	675
a_{uu}^c (MeV/fm ²)	52.9	55.7	56.4	60.3
a_{us}^c (MeV/fm ²)	76.0	72.1	104.1	98.8
a_{uu}^{c0} (MeV)	-51.7	-56.4	-86.4	-91.8
a_{us}^{c0} (MeV)	-68.5	-63.0	-123.1	-116.8

$$f_{chv} = \frac{3}{5}(f_{NN\rho} - 4g_{NN\rho}). \quad (32)$$

In the Nijmegen model D, $g_{NN\rho} = 2.09$ and $f_{NN\rho} = 17.12$ [22]. From the two equations above, we get $g_{chv} = 2.09$ and $f_{chv} = 5.26$. In this work, we neglect the tensor coupling part of the vector meson field as did by Riska and Brown [21], and take the coupling constant for vector coupling of the vector-meson field to be $g_{chv} = 2.351$ as the same we used in the NN scattering calculation [10], which is a little bit smaller than the value used in Ref. [21], but slightly larger than the value obtained from the $NN\rho$ coupling constant of Nijmegen model D [22]. The masses of all the mesons are taken to be the experimental values, except for the σ meson, whose mass is treated as an adjustable parameter. We chose $m_\sigma = 675$

MeV as the same in the original chiral SU(3) quark model [11], where it is fixed by the S -wave KN phase shifts. The cutoff radius Λ^{-1} is taken to be the value close to the chiral symmetry breaking scale [23, 24, 25, 26]. After the parameters of chiral fields are fixed, the coupling constants of OGE, g_u and g_s , can be determined by the mass splits between N , Δ and Σ , Λ , respectively. The confinement strengths a_{uu}^c , a_{us}^c , and a_{ss}^c are fixed by the stability conditions of N , Λ , and Ξ and the zero-point energies a_{uu}^{c0} , a_{us}^{c0} , and a_{ss}^{c0} by fitting the masses of N , Σ , and $\Xi + \bar{\Omega}$, respectively.

TABLE II: The masses of octet and decuplet baryons.

	N	Σ	Ξ	Λ	Δ	Σ^*	Ξ^*	Ω
Theor.	939	1194	1335	1116	1232	1370	1511	1684
Expt.	939	1194	1319	1116	1232	1385	1530	1672

In the calculation, η and η' mesons are mixed by η_1 and η_8 with the mixing angle θ^{PS} taken to be the usual value -23° . ω and ϕ mesons consist of $\sqrt{1/2}(u\bar{u} + d\bar{d})$ and $(s\bar{s})$, respectively, i.e., they are ideally mixed by ω_1 and ω_8 with the mixing angle $\theta^V = 35.264^\circ$. For the KN case, we also consider the mixing between σ_0 and σ_8 . The mixing angle θ^S is an open issue because the structure of the σ meson is still unclear and controversial. We adopt two possible values as in our previous works [11, 12], one is 35.264° which means that σ and f_0 [In our previous works f_0 was named ϵ and a_0 was named σ'] are ideally mixed by σ_0 and σ_8 , and the other is -18° which is provided by Dai and Wu based on their recent investigation of a dynamically spontaneous symmetry breaking mechanism [27]. In both of these two cases, the attraction of the σ meson can be reduced a lot, and thus we can get reasonable S -wave KN phase shifts.

The model parameters are summarized in Table I. The masses of octet and decuplet baryons obtained from the extended chiral SU(3) quark model are listed in Table II.

C. Dynamical study of the KN phase shifts

With all parameters determined in the extended chiral SU(3) quark model, the KN phase shifts can be dynamically studied in the frame work of the RGM. The wave function of the

five quark system is of the following form:

$$\Psi = \mathcal{A}[\hat{\phi}_N(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\hat{\phi}_K(\boldsymbol{\xi}_3)\chi(\mathbf{R}_{NK})], \quad (33)$$

where $\boldsymbol{\xi}_1$ and $\boldsymbol{\xi}_2$ are the internal coordinates for the cluster N , and $\boldsymbol{\xi}_3$ the internal coordinate for the cluster K . $\mathbf{R}_{NK} \equiv \mathbf{R}_N - \mathbf{R}_K$ is the relative coordinate between the two clusters, N and K . The $\hat{\phi}_N$ is the antisymmetrized internal cluster wave function of N , and $\chi(\mathbf{R}_{NK})$ the relative wave function of the two clusters. The symbol \mathcal{A} is the antisymmetrizing operator defined as

$$\mathcal{A} \equiv 1 - \sum_{i \in N} P_{i4} \equiv 1 - 3P_{34}. \quad (34)$$

Substituting Ψ into the projection equation

$$\langle \delta\Psi | (H - E) | \Psi \rangle = 0, \quad (35)$$

we obtain the coupled integro-differential equation for the relative function χ as

$$\int [\mathcal{H}(\mathbf{R}, \mathbf{R}') - E\mathcal{N}(\mathbf{R}, \mathbf{R}')] \chi(\mathbf{R}') d\mathbf{R}' = 0, \quad (36)$$

where the Hamiltonian kernel \mathcal{H} and normalization kernel \mathcal{N} can, respectively, be calculated by

$$\begin{Bmatrix} \mathcal{H}(\mathbf{R}, \mathbf{R}') \\ \mathcal{N}(\mathbf{R}, \mathbf{R}') \end{Bmatrix} = \left\langle [\hat{\phi}_N(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\hat{\phi}_K(\boldsymbol{\xi}_3)]\delta(\mathbf{R} - \mathbf{R}_{NK}) \left| \begin{Bmatrix} H \\ 1 \end{Bmatrix} \right. \right. \right. \right. \left. \left. \left. \left. \mathcal{A} \left[[\hat{\phi}_N(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\hat{\phi}_K(\boldsymbol{\xi}_3)]\delta(\mathbf{R}' - \mathbf{R}_{NK}) \right] \right\rangle \right\rangle \right\rangle \right\rangle. \quad (37)$$

Eq. (36) is the so-called coupled-channel RGM equation. Expanding unknown $\chi(\mathbf{R}_{NK})$ by employing well-defined basis wave functions, such as Gaussian functions, one can solve the coupled-channel RGM equation for a bound-state problem or a scattering one to obtain the binding energy or scattering phase shifts for the two-cluster systems. The details of solving the RGM equation can be found in Refs. [11, 28, 29, 30].

III. RESULTS AND DISCUSSIONS

In the extended chiral SU(3) quark model, the coupling of quarks and vector-meson field is considered, and thus the coupling constants of OGE are greatly reduced by fitting the

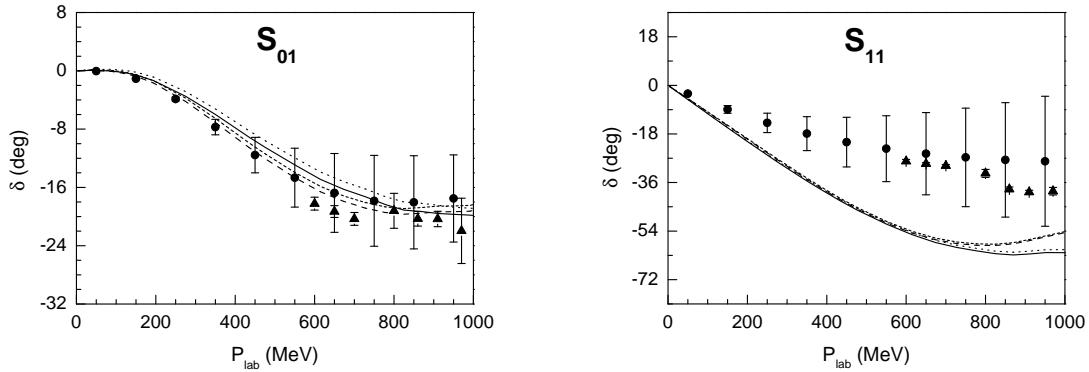


FIG. 1: KN S -wave phase shifts as a function of the laboratory momentum of kaon meson. The solid and dotted curves represent the results obtained in the extended chiral $SU(3)$ quark model by considering $\theta^S = 35.264^\circ$ and -18° , respectively. The dashed and short-dashed curves show the phase shifts of the original chiral $SU(3)$ quark model by taking θ^S as 35.264° and -18° , respectively. Experimental phase shifts are taken from Refs. [31] (circles) and [32] (triangles).

mass difference between N , Δ and Λ , Σ . From Table I, one can see that for both set I and set II, $g_u^2 = 0.0748$ and $g_s^2 = 0.0001$, which are much smaller than the values of the original chiral $SU(3)$ quark model ($g_u^2 = 0.7704$ and $g_s^2 = 0.5525$). This means that the OGE, which plays an important role of the KN short-range interaction in the original chiral $SU(3)$ quark model, is now nearly replaced by the vector-meson exchanges. In other words, in the KN system the mechanisms of the quark-quark short-range interactions of these two models are totally different.

A RGM dynamical calculation of the S -, P -, D -, and F -wave KN phase shifts with isospin $I = 0$ and $I = 1$ is performed, and the numerical results are shown in Figs. 1–4. Here we use the conventional partial wave notation: the first subscript denotes the isospin quantum number and the second one twice of the total angular momentum of the KN system. For comparison the phase shifts calculated in the original chiral $SU(3)$ quark model are also shown in these figures.

Let's first concentrate on the S -wave results (Fig. 1). In a previous quark model study [5] where the π and σ boson exchanges as well as the OGE and confining potential are taken as the quark-quark interaction, the authors concluded that a consistent description of the S -wave KN phase shifts in both isospin $I = 0$ and $I = 1$ channels simultaneously is not possible. Another recent work in a constituent quark model based on the RGM calculation

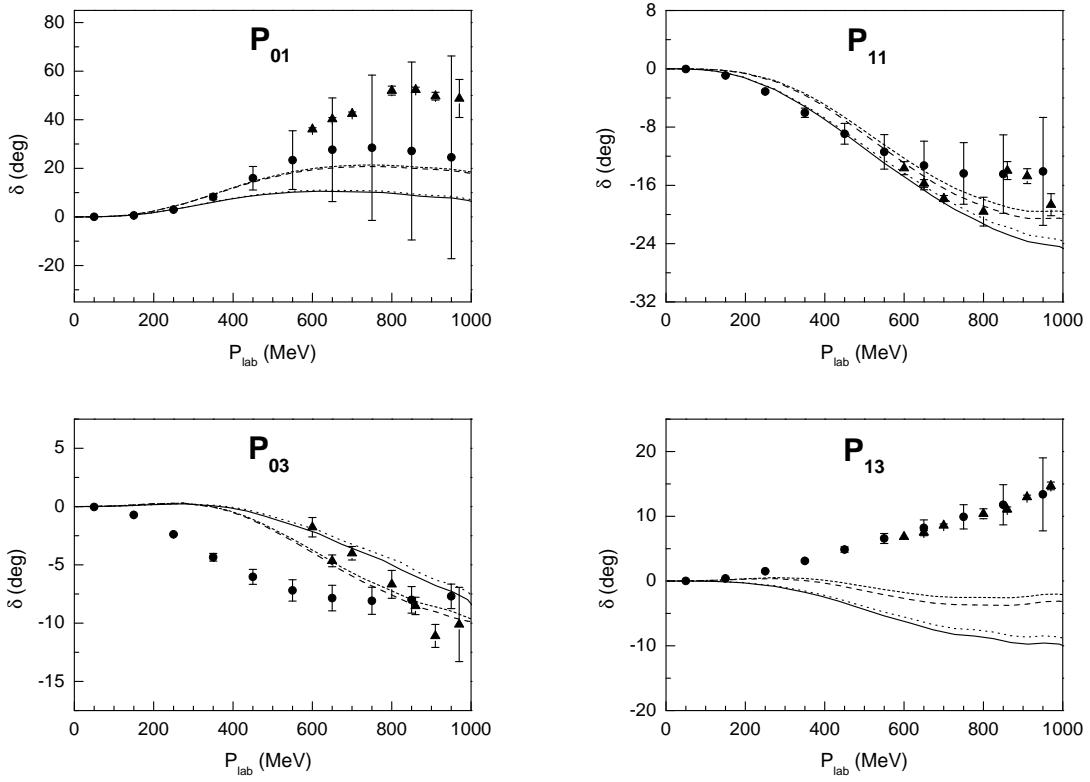


FIG. 2: KN P -wave phase shifts. Same notation as in Fig. 1.

gave an opposite sign of the S_{01} channel phase shifts [7]. From Fig. 1 one can see that we obtain a successful description of the S_{01} channel phase shifts, and for the S_{11} partial wave, similar to that obtained in the original chiral SU(3) model, the trend of the theoretical phase shifts is also in agreement with the experiment. Since there is no contribution coming from the spin-orbit coupling in the S -wave, only the central force of the quark-quark interaction can enter in the scattering process, thus it plays a dominantly important role. To understand the contributions of various chiral fields to the KN interaction, in Fig. 5 we show the central force diagonal matrix elements of the generator coordinate method (GCM) calculation [28] of the σ , a_0 , π , ρ , and ω boson exchanges in the extended chiral SU(3) quark model, which can describe the interaction between two clusters N and K qualitatively. In Fig. 5, s denotes the generator coordinate and $V(s)$ is the effective boson-exchange potential between the two clusters. Form this figure we can see that the σ exchange always offers attraction and ω exchange offers repulsion in both isospin $I = 0$ and $I = 1$ channels. This is reasonable since the σ and ω exchanges are isospin independent. Contrarily, the a_0 , π , and

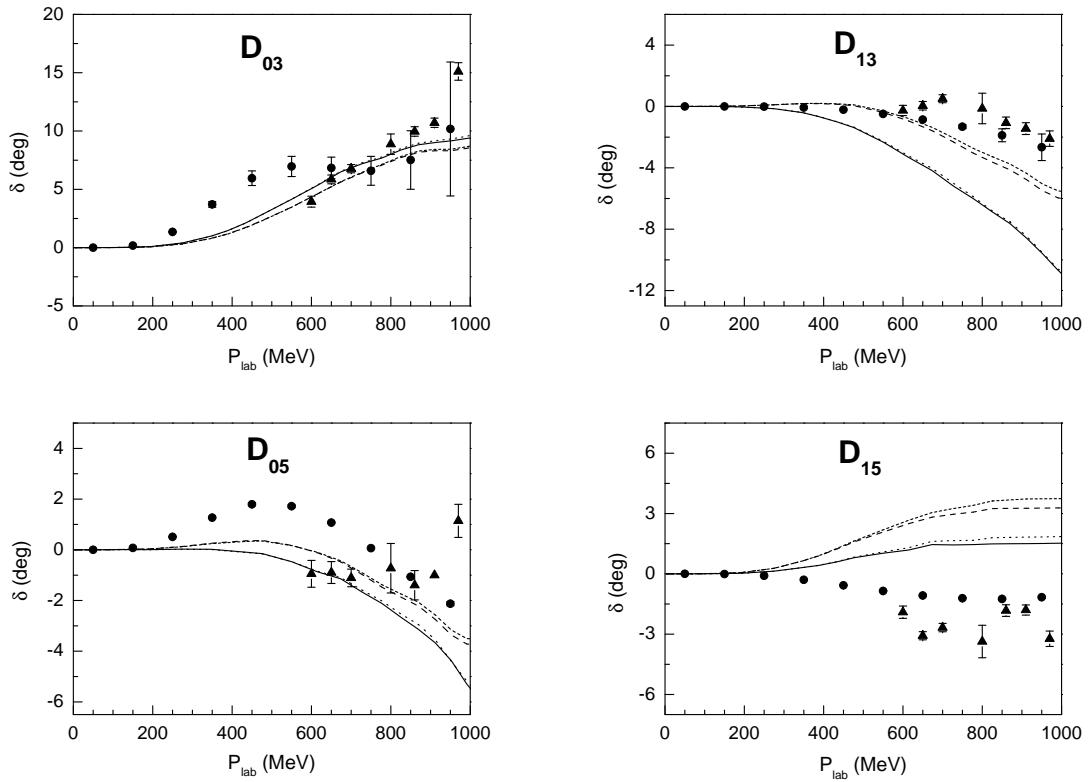


FIG. 3: KN D -wave phase shifts. Same notation as in Fig. 1.

ρ exchanges are isospin dependent. In the S_{01} partial wave the a_0 exchange offers repulsive and ρ exchange offers a little attractive, while in the S_{11} partial wave the a_0 exchange offers a little attraction and ρ exchange offers repulsion. In both of these two channels the π exchange, existing due to the quark exchange required by the Pauli principle, always offers much strong repulsion though the repulsion strength is different. This means that the one-pion exchange is important and cannot be neglected on the quark level, which is quite different from the works on the hadron level where the one-pion exchange is absent in the KN interaction.

Now look at the P -wave KN phase shifts (Fig. 2). The results for the P_{13} channel, which are too repulsive in the original chiral SU(3) quark model when the laboratory momentum of the kaon meson is greater than 300 MeV, the same case as in Black's previous work [4], are now much more repulsive in the extended chiral SU(3) quark model. For the other channels the results in both these two models are similar to each other. Comparing with Ref. [7], we get correct signs and proper magnitudes of P_{11} and P_{03} waves in both the extended chiral

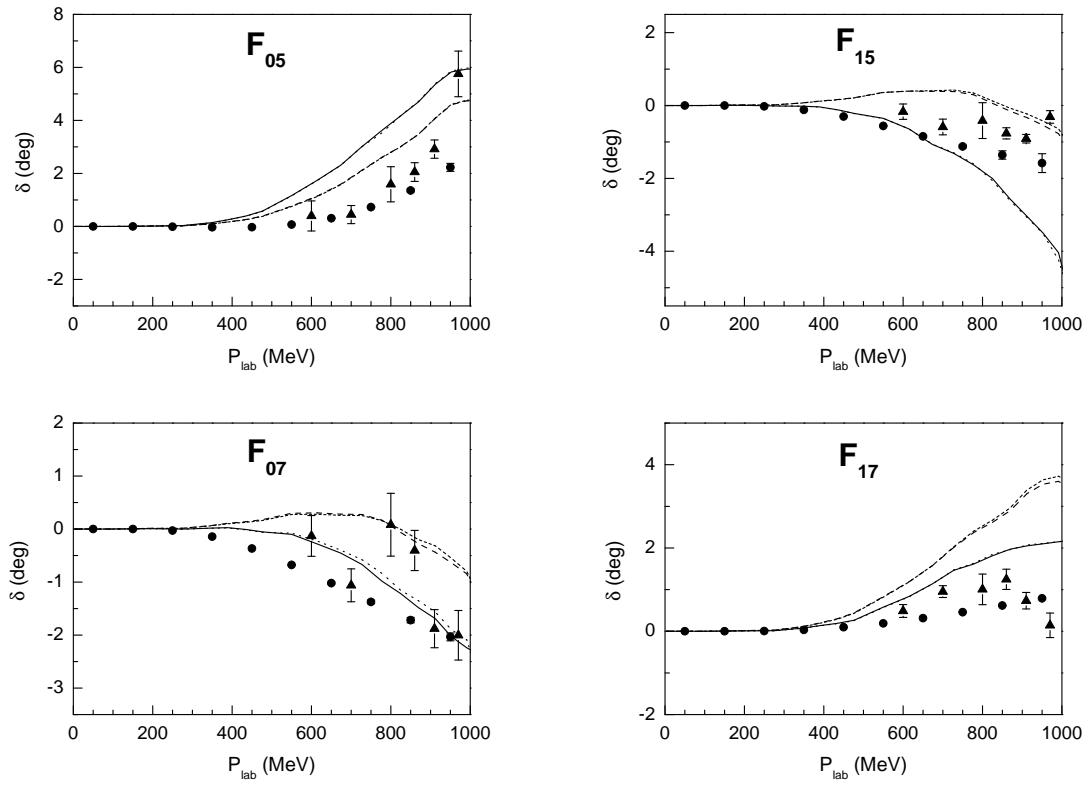


FIG. 4: KN F -wave phase shifts. Same notation as in Fig. 1.

$SU(3)$ quark model and the original chiral $SU(3)$ quark model.

For higher-angular-momentum partial waves (Figs. 3–4), the theoretical phase shifts of D_{15} and F_{17} in the extended chiral $SU(3)$ quark model are improved in comparison with those obtained from the original chiral $SU(3)$ quark model, while in the case of the D_{13} the situation is somewhat less satisfying. For the other channels, the trends of the calculated phase shifts in both these two models are all in qualitative agreement with the experiment. Comparing with Ref. [7], in both these two models, we can get correct signs of D_{13} , D_{05} , F_{15} , and F_{07} waves, and for D_{03} and D_{15} channels we also obtain a considerable improvement on the theoretical phase shifts in the magnitude.

As discussed in Refs. [11, 12], the annihilation interaction is not clear and its influence on the phase shifts should be examined. We omit the annihilation part entirely to see its effect and find that the numerical phase shifts only have very small changes. This is because in the KN system the annihilations to gluons and vacuum are forbidden and $u(d)\bar{s}$ can only annihilate to K and K^* mesons. This annihilation part originating from the S -channel acts

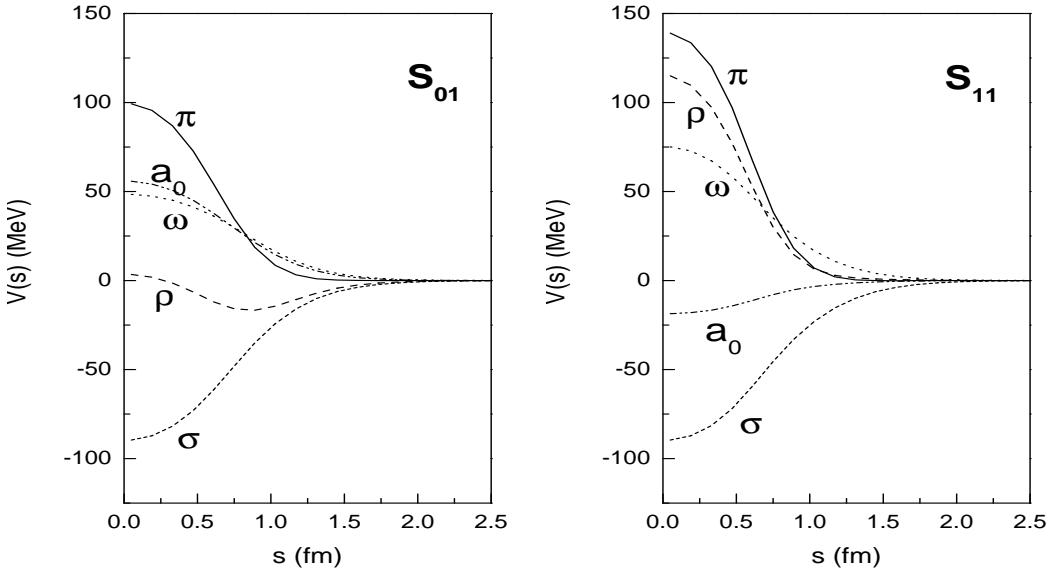


FIG. 5: The GCM matrix elements of σ , a_0 , π , ρ , and ω exchanges in the extended chiral SU(3) quark model.

in the very short range, so that it plays a negligible role in the KN scattering process.

The other thing we would like to mention is that our results of KN phase shifts are independent of the confinement potential in the present one-channel two-color-singlet-cluster calculation. Thus the numerical results will almost remain unchanged even the color quadratic confinement is replaced by the color linear one.

From the above discussion, one sees that though the mechanisms of the quark-quark short-range interactions are totally different in the original chiral SU(3) quark model and the extended chiral SU(3) quark model, the theoretical KN phase shifts of S , P , D , and F waves in these two models are very similar to each other. Comparing with others' previous quark model studies, we can obtain a considerable improvement for many channels. However, in the present work the P_{13} and D_{15} partial waves have not yet been satisfactorily described. In this sense, one can say that the present quark model still has some difficulties to describe the KN scattering well enough for all of the partial waves. It should be studied in future work the possibility of that if there are some physical ingredients missing in our quark model investigations, as well as the relativistic effects and the nonelastic channel effects on the KN phase shifts.

By the way, to study the short-range quark-quark interaction more extensively, or on the other words, to examine whether the OGE or the vector meson exchange governs the short

range interaction between quarks, besides the KN systems the $\bar{K}N$ is also an interesting case, since there is a close connection of the vector-meson exchanges between the KN and $\bar{K}N$ interactions due to G -parity transition. Specially, the repulsive ω exchange changes sign for $\bar{K}N$, because of the negative G parity of the ω meson, and becomes attractive. However, one should note that the treatment of the $\bar{K}N$ channel is more complicated than the KN system since it involves s -channel gluon and vacuum contributions. Still the extension of our chiral quark model to incorporate the gluon and vacuum annihilations in the $\bar{K}N$ system would be a very interesting new development. Investigations along this line are planned for the future.

IV. SUMMARY

In this paper, we extend the chiral $SU(3)$ quark model to include the coupling between quarks and vector chiral field. The OGE which dominantly governed the short-range quark-quark interactions in the original chiral $SU(3)$ quark model is now nearly replaced by the vector-meson exchange. Using this model, a dynamical calculation of the S -, P -, D -, and F -wave KN phase shifts is performed in the isospin $I = 0$ and $I = 1$ channels by solving a RGM equation. The calculated phase shifts of different partial waves are similar to those given by the original chiral $SU(3)$ quark model. Comparing with Ref. [7], a recent RGM calculation in a constituent quark model, we can obtain correct signs of several partial waves and a considerable improvement in the magnitude for many channels. Nevertheless, in the present work we do not obtain a satisfactory improvement for the P_{13} and D_{15} partial waves, of which the theoretical phase shifts are too much repulsive and attractive respectively when the laboratory momentum of the kaon meson is greater than 300 MeV. Further the effects of the coupling to the inelastic channels and hidden color channels will be considered and the interesting and more complicated $\bar{K}N$ system will be investigated in future work.

Acknowledgments

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- [1] R. Buettgen, K. Holinde, A. Mueller-Groeling, J. Speth, and P. Wyborny, Nucl. Phys. **A506**, 586 (1990).
- [2] D. Hadjimichef, J. Haidenbauer, and G. krein, Phys. Rev. C **66**, 055214 (2002).
- [3] T. Barnes and E.S. Swanson, Phys. Rev. C **49**, 1166 (1994).
- [4] N. Black, J. Phys. G **28**, 1953 (2002).
- [5] B. Silvestre-Brac, J. Labarsouque, and J. Leandri, Nucl. Phys. **A613**, 342 (1997).
- [6] S. Lemaire, J. Labarsouque, and B. Silvestre-Brac, Nucl. Phys. **A700**, 330 (2002).
- [7] S. Lemaire, J. Labarsouque, and B. Silvestre-Brac, Nucl. Phys. **A714**, 265 (2003).
- [8] H.J. Wang, H. Yang, and J.C. Su, Phys. Rev. C **68**, 055204 (2003).
- [9] Z.Y. Zhang, Y.W. Yu, P.N. Shen, L.R. Dai, A. Faessler, and U. Straub, Nucl. Phys. **A625**, 59 (1997).
- [10] L.R. Dai, Z.Y. Zhang, Y.W. Yu, and P. Wang, Nucl. Phys. **A727**, 321 (2003).
- [11] F. Huang, Z.Y. Zhang, and Y.W. Yu, Phys. Rev. C **70**, 044004 (2004).
- [12] F. Huang and Z.Y. Zhang, Phys. Rev. C **70**, 064004 (2004).
- [13] L.Ya. Glozman, D.O. Riska, Phys. Rept. **268**, 263 (1996).
- [14] L.Ya. Glozman, Nucl. Phys. **A663**, 103c (2000).
- [15] N. Isgur, Phys. Rev. D **61**, 118501 (2000).
- [16] N. Isgur, Phys. Rev. D **62**, 054026 (2000).
- [17] K.F. Liu *et al.*, Phys. Rev. D **59**, 112001 (1999).
- [18] K.F. Liu *et al.*, Phys. Rev. D **61**, 118502 (2000).
- [19] Fl. Stancu, S. Pepin, and L.Ya. Glozman, Phys. Rev. C **56**, 2779 (1997).
- [20] K. Shimizu and L.Ya. Glozman, Phys. Lett. B **477**, 59 (2000).
- [21] D.O. Riska and G.E. Brown, Nucl. Phys. **A679**, 577 (2001).
- [22] M.M. Nagels, T.A. Rijken, and J.J. de Swart, Phys. Rev. D **12**, 744 (1975).
- [23] I.T. Obukhovsky and A.M. Kusainov, Phys. Lett. B **238**, 142 (1990).

- [24] A.M. Kusainov, V.G. Neudatchin, and I.T. Obukhovsky, Phys. Rev. C **44**, 2343 (1991).
- [25] A. Buchmann, E. Fernandez, and K. Yazaki, Phys. Lett. B **269**, 35 (1991).
- [26] E.M. Henley and G.A. Miller, Phys. Lett. B **251**, 453 (1991).
- [27] Y.B. Dai and Y.L. Wu, Eur. Phys. J. C **39**, S1 (2005).
- [28] K. Wildermuth and Y.C. Tang, *A Unified Theory of the Nucleus* (Vieweg, Braunschweig, 1977).
- [29] M. Kamimura, Suppl. Prog. Theor. Phys. **62**, 236 (1977).
- [30] M. Oka and K. Yazaki, Prog. Theor. Phys. **62**, 556 (1981).
- [31] J.S. Hyslop, R.A. Arndt, L.D. Roper, and R.L. Workman, Phys. Rev. D **46**, 961 (1992).
- [32] K. Hashimoto, Phys. Rev. C **29**, 1377 (1984).